

Final-state interactions effects in neutral-current neutrino and antineutrino cross sections at MiniBooNE kinematics

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The predictions of different relativistic descriptions of final-state interactions are compared with the neutral current elastic neutrino and antineutrino-nucleus differential cross sections recently measured by the MiniBooNE Collaboration. The results of the relativistic Green's function model describe the data without the need to increase the standard value of the nucleon axial mass.

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I. INTRODUCTION

The MiniBooNE Collaboration at FermiLab has reported measurements of the neutral-current elastic (NCE) flux-averaged differential neutrino [1] and, more recently, antineutrino [2] cross sections on CH_2 as a function of the four-momentum transferred squared Q^2 . Measurements of the neutrino and antineutrino charged-current quasielastic (CCQE) cross sections on carbon have also been reported in [3, 4].

At the few GeV energy region considered in the MiniBooNE experiments theoretical models based on the impulse approximation (IA) are usually unable to reproduce the experimental cross sections [5–8] unless calculations are performed with a value of the nucleon axial mass M_A significantly larger ($M_A \sim 1.20 \div 1.40 \text{ GeV}/c^2$) than the world average value from the deuterium data of $M_A \simeq 1.03 \text{ GeV}/c^2$ [9, 10]. This has been viewed as an indication that the reaction can have significant contributions from effects beyond the IA. A careful analysis of all nuclear effects and of the relevance of multinucleon emission and of some non-nucleonic contributions is required for a deeper understanding of the reaction dynamics [11–20].

Models developed for quasielastic (QE) electron scattering [21, 22] and able to successfully describe electron scattering data can provide a useful tool to study neutrino-induced reactions. A reliable description of the effects of final-state interactions (FSI) between the ejected nucleon and the residual nucleus is very important for the comparison with data [21–28]. The relevance of FSI has been clearly stated in the case of the exclusive ($e, e'p$) reaction within the distorted-wave impulse approximation (DWIA), where the use of a complex optical potential (OP) whose imaginary part produces an absorption that reduces the calculated cross section is essential to reproduce the data. In the case of the inclusive (e, e') reaction, as well as of CCQE and NCE neutrino scattering, the use of the

DWIA with an absorptive complex OP is not correct and different approaches have been adopted. In the relativistic plane-wave impulse approximation (RPWIA) FSI are neglected. In other approaches based on the IA FSI are incorporated in the final nucleon state either retaining only the real part of the relativistic optical potential (rROP), or using the same relativistic mean field potential considered in describing the initial nucleon state (RMF) [29, 30].

In the relativistic Green's function (RGF) model the components of the nuclear response are written in terms of matrix elements of the same type as the DWIA ones of the exclusive ($e, e'p$) process, but involve eigenfunctions of the OP and of its Hermitian conjugate, where the imaginary part has an opposite sign and gives in one case an absorption and in the other case a gain of strength. A detailed description of the model can be found in our previous work [31–37].

In [38, 39] we have already discussed the results of different relativistic descriptions of FSI for NCE scattering averaged over the ν and $\bar{\nu}$ MiniBooNE flux. We note that the RGF is appropriate for an inclusive process like CCQE, whereas the NCE scattering is a semi-inclusive process where the final neutrino cannot be detected and only the final nucleon is measured. As a consequence, the RGF may include channels which are not present in the experimental NCE measurements, but it can also recover important contributions which are not taken into account by other models based on the IA. In comparison with the MiniBooNE NCE neutrino scattering data, the DWIA and RMF generally underpredict the experimental cross section, while the RGF results are in reasonable agreement with the data. In this report we extend the comparison to MiniBooNE NCE antineutrino data which have only recently become available.

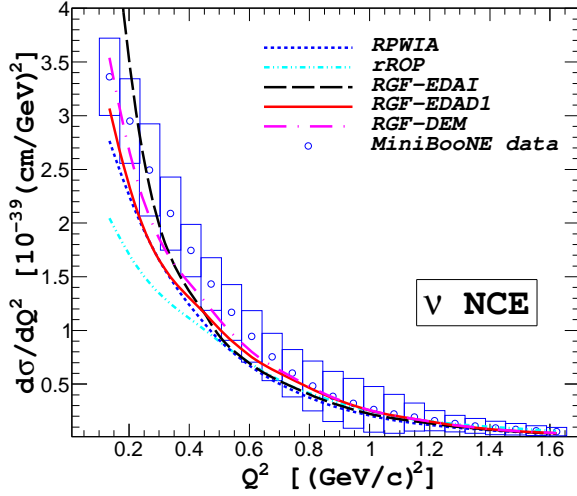


Figure 1. (Color online) NCE flux-averaged ($\nu N \rightarrow \nu N$) cross section as a function of Q^2 . The data are from [1].

II. RESULTS AT MINIBOOONE KINEMATICS

In all the calculations we have adopted the standard value of the axial mass, i.e., $M_A = 1.03$ GeV/ c^2 , and we have neglected strangeness effects in the nucleon form factors. The bound nucleon states are taken as self-consistent Dirac-Hartree solutions derived within a relativistic mean field approach using a Lagrangian containing σ , ω , and ρ mesons [40–44].

In the RGF calculations we have used three parametrizations for the relativistic OP of ^{12}C : the Energy-Dependent and A-Dependent EDAD1 (the E represents the energy and the A the atomic number) and the Energy-Dependent but A-Independent EDAI OPs of [45], and the more recent Democratic (DEM) OP of [46]. EDAI is a single-nucleus parametrization, which is constructed to better reproduce the elastic proton- ^{12}C phenomenology. In contrast, EDAD1 and DEM depend on the atomic number A and are obtained through a fit to more than 200 data sets of elastic proton-nucleus scattering data on a wide range of nuclei that is not limited to doubly closed shell nuclei. In [47, 48] the evolution of QE electron scattering cross sections along different isotopic and isotonic chains evaluated within the RGF with the DEM OP is presented: the different number of nucleons along the chains produces different OPs, but the results for the cross sections are always reasonable, even for nuclei with large asymmetry between the number of neutrons and protons.

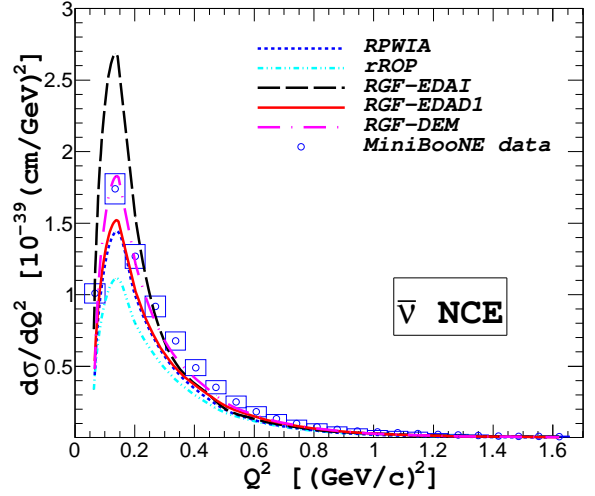


Figure 2. (Color online) The same as in Fig. 1, but for ($\bar{\nu} N \rightarrow \bar{\nu} N$) cross section. The data are from [2].

In Fig. 1 our NCE ($\nu N \rightarrow \nu N$) cross sections are displayed as a function of $Q^2 = 2m_N \sum_i T_i$, where Q^2 is defined assuming the target nucleon at rest, m_N is the nucleon mass, and $\sum_i T_i$ is the total kinetic energy of the outgoing nucleons. These results have already been published in [38, 39] and are presented here again for completeness. The RPWIA results, where FSI are neglected, show a satisfactory, although not perfect, agreement with the magnitude of the data whereas the rROP ones, which are calculated retaining only the real part of the EDAI potential, underestimate the data but for $Q^2 \geq 0.6$ (GeV/ c) 2 . The RGF cross sections are in better agreement with the data. The differences between the RGF results are due to the different imaginary parts of the relativistic OPs adopted in the calculations, which produce large differences in the neutrino-nucleus cross sections evaluated at fixed neutrino energies and at small values of the outgoing nucleon kinetic energy,

In Fig. 2 we present our flux-averaged NCE ($\bar{\nu} N \rightarrow \bar{\nu} N$) cross sections as a function of Q^2 . In [39] we already presented theoretical predictions for antineutrino cross sections using the set of efficiency coefficients given in [1] for neutrino scattering. The selection for the antineutrino NCE sample is slightly different from the neutrino one and the efficiencies are only approximately similar. The results displayed in Fig. 2 are evaluated with the correct efficiencies for antineutrinos. Also in the antineutrino case the rROP cross sections are lower than the RPWIA ones, whereas the RGF produces larger cross sections. The data are underpredicted by the rROP and satisfactorily de-

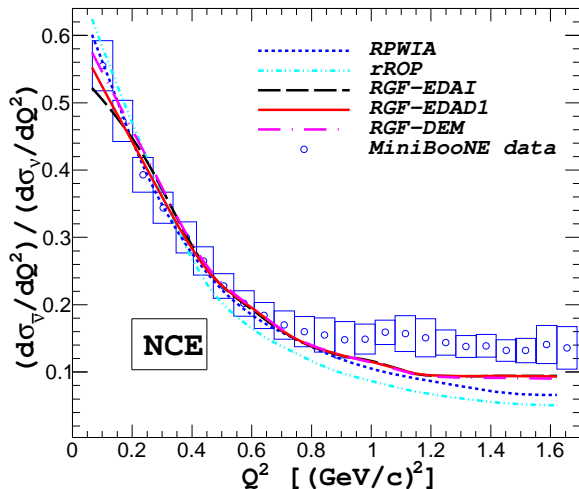


Figure 3. (Color online) Ratio of the $\bar{\nu}$ to ν NCE scattering cross section with total error. The data are from [2].

scribed by the RPWIA. A better agreement with the data is generally provided by the RGF, in particular when the DEM OP is adopted. The RGF-EDAI results are enhanced at $Q^2 \approx 0.1$ (GeV/c) 2 and the RGF-EDAD1 cross sections are similar to the RPWIA ones in the entire kinematical range of MiniBooNE $\bar{\nu}$ flux. All the models are able to reasonably reproduce the first datum at $Q^2 \approx 0.06$ (GeV/c) 2 .

In Fig. 3 we show our results for the ratio of the $\bar{\nu}$ to ν NCE scattering cross section. Ratios of cross sections are particularly interesting, owing to the fact that in the ratios distortion effects are largely reduced and different descriptions of FSI are expected to produce similar results [39, 49, 50]. From the experimental point of view, both ν and $\bar{\nu}$ NCE measurements were made in the same beam-line and with the same detector but with opposite horn polarities [1, 2, 51]. Despite the fact that the experimental ν and $\bar{\nu}$ fluxes are not identical, the ratio of the two cross sections should minimize the errors and provide a useful observable to test various theoretical models.

In Fig. 3 all the models give, as it was expected, very close results. In particular, the RGF results are practically independent of the parametrization adopted for the OP; small differences can be seen only at very low Q^2 , but all the results are within the experimental errors. At large Q^2 all

the results slightly underestimate the data. This is related to the fact that the $\bar{\nu}$ cross sections in Fig. 2 are underestimated for $Q^2 \geq 1$ (GeV/c) 2 , whereas the ν cross sections in Fig. 1 are within the error bars in the entire range of Q^2 .

III. CONCLUSIONS

The predictions of different relativistic descriptions of FSI have been compared with the NCE MiniBooNE data for ν and $\bar{\nu}$ -nucleus scattering.

The RGF results are able to describe the data, both for ν and $\bar{\nu}$ scattering, without the need to increase the standard value of the axial mass. Visible differences on the RGF cross sections at low values of Q^2 are produced by the use of different parametrizations of the phenomenological OP. The best agreement with the data is given by the RGF-DEM results. In the ratio of the $\bar{\nu}$ to ν NCE scattering cross sections FSI effects are strongly reduced and the RGF results are practically independent of the choice of the OP. The experimental ratio is reasonably described when $Q^2 \leq 1$ (GeV/c) 2 and slightly underestimated when $Q^2 \geq 1$ (GeV/c) 2 by all the RGF results.

Different and independent models have confirmed the important role of contributions other than direct one-nucleon emission. Owing to the flux-average procedure, ν -nucleus reactions at MiniBooNE can have important contributions from effects beyond the IA in some kinematic regions where the experimental ν flux has significant strength [7, 52]. Although contributions like, e.g., rescattering processes of the nucleon, non-nucleonic Δ excitations, or multinucleon processes are not included explicitly in the RGF model, they can be recovered, at least to some extent, by the imaginary part of the phenomenological OP. The use of such a phenomenological ingredient, however, does not allow us to explain in detail the origin of the enhancement of the RGF results with respect to the results of other models based on the IA. At present, lacking a phenomenological OP which exactly fulfills the dispersion relations in the whole energy region of interest, the RGF predictions are not univocally determined from the elastic phenomenology. A better determination of a relativistic OP, which closely fulfills the dispersion relations, deserves further investigation.

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